ENVIRONMENTAL CHANGES IN RELATION TO TREE DEATH ALONG THE KUISEB RIVER IN THE NAMIB DESERT

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ABSTRACT The Namib Desert is located along the western coast of Namibia and is affected by the cold Benguela Current. Although forest is distributed along the Kuiseb River in the Namib Desert, many trees are almost dead in some areas. The aim of this research was to clarify the relationship between environmental changes and tree death. The results of the survey are summarized as follows: (1) Many dead trees are located on the riverbanks made of dune sand, which are about 1 m high. (2) Dead trees are located in transitional areas where a northward protrusion of the southern shore is followed by a southward protrusion of the northern shore along the course of the river, in proximity to a sand dune. (3) Floods have eroded the noses of advancing sand dunes of the upper stream and have caused tree death by depositing sand. (4) The date of tree death has been estimated between the late 1970s and the early 1980s by ^{14}C dating. (5) Flood days numbered 33 per year from 1962 to 1975 and 2.7 from 1976 to 1985. The remaining thick sand layer, deposited by the last flood, may be the cause of tree death, given that there was drastic decrease in floods since 1976. (6) Tree death has greatly affected people's lives along the Kuiseb River because they depend on riverside forests as a source of shade, shelter, fuel, and food for humans and livestock.

Key Words: Kuiseb River; Namib Desert; Tree death; Flood decrease; Sand deposits; Humans.

INTRODUCTION

In Namibia, a country that contains a large desert area, desertification is a serious problem because it directly affects people's lives. Indicators of desertification in Namibia include the lowering of groundwater tables, soil erosion, loss of woody vegetation (trees), loss of grasses and shrubs (i.e., bare soil), a decrease in preferred grasses and shrubs, bush encroachment, an increase in soil salt content (salinity), and a decrease in soil fertility (Seely & Jacobson, 1986).

The forests along the banks of the Kuiseb River in the Namib Desert are partially dead. A common characteristic of areas of tree death is that the riverbank (about 1 m in height) is composed of dune sand; additionally, the curvature of the river changes from a northward to a southward projection, and is close to sand dunes. It has been surmised that the tree death is relatively recent, in that trees' ages have been found to be fairly consistent, about 100 to 350 years, irrespective of their vital status. The aim of this study was to clarify the reasons for the recent tree death in this region and to present the characteristics common to such areas.

STUDY AREA AND METHODS

I. Study Area

The research was performed near Gobabeb along the Kuiseb River in the Namib Desert in August, November, and December 2002; in March, August, November, and December 2003; and in August 2004 (Figs. 1 & 2). In Gobabeb, although the annual rainfall is only 27 mm, fog-water precipitation is 31 mm (Lancaster *et al*., 1984). Extending inland for tens of kilometers on many mornings, the fog is densest at an elevation of 300 to 600 m. The fog is at its densest and fog-water precipitation is at its greatest about 40 km inland from the coast, because the altitude of the Namib Desert gradually increases from the coast eastward. Fog arises, on average, 37 days per year (1976–1981) in Gobabeb and constitutes the most important water supply for animals and plants in the Namib Desert (Lancaster *et al*., 1984). The daily mean temperature per month is highest (24.8°C) in March and lowest (17.6°C) in August, and annual mean temperature is 21.1°C (Lancaster *et al*., 1984). More than 90% of the annual rainfall occurs in the rainy season, from January to April. The coastal area is cool; the highest monthly mean temperature, 17.7°C, is in February and the lowest, 12.9°C, is in October. The annual mean temperature is only 15.5°C, owing to the cold Benguela Current.

Fig. 2. Dead trees along the Kuiseb River.

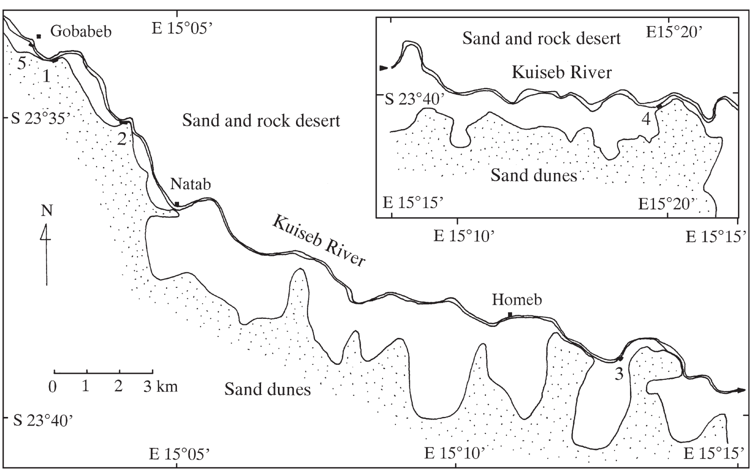

Fig. 1. Study sites. Sites 1–4: Sites with many dead trees; Site 5: Control site.

II. Methods

The study examined 50 km along the Kuiseb River; regions covered by many dead trees were investigated for their vegetation, topography, and soil. Quadrants were established for Sites 1 through 4 (Site 1: 100 m × 200 m; Site 2: 30 m × 210 m; Site 3: 18 m × 120 m; and Site 4: 25 m × 60 m), typified by extensive tree death; Site 5 (15 m × 75 m), however, was occupied by mostly healthy trees. Tree height and diameter at breast height of *Faidherbia albida* and *Acacia erioloba* were investigated for each quadrant. Although *Faidherbia albida* was formerly called *Acacia albida*, *Faidherbia* is quite different from *Acacia,* especially in terms of wood anatomy and pollen morphology, and the fact that it remains leafless for much of the wet season, only coming into leaf in the early dry season (Wyk *et al*., 2000). *Faidherbia albida* and *Acacia erioloba* were selected to investigate the relationship between tree height and diameter at breast height because they account for more than 90% of all trees in the study area and are morphologically similar. The quadrant of Site 1 was established to include the slope of the sand dune, a small terrace (i.e., river bank) formed by redeposit of dune sand, and the slope below the terrace. The quadrants of Sites 2 through 4 were established to include a small terrace (river bank) formed by dune sand.

Surface soil in the forest along the river is generally a dull yellowish brown (10YR5/3, 10YR5/4, and 10YR4/3), and the dune sand is generally a bright reddish brown (5YR5/6) to dull brown color (7.5YR5/4). Therefore, the depth of sand transported from the sand dunes can easily be obtained by measuring the distance from the land surface to the top of the dull yellowish-brown layer (10YR5/3, 10YR5/4, and 10YR4/3) (Fig. 21). In addition, the texture of the dull yellowish-brown soil (i.e., sandy loam) is quite different from that of the dune sand.

Tree diameters were measured at their bases in cases where the trees appeared partially buried. The vital status of trees was divided into four groups: healthy growing, unhealthy growing, dying, and dead. Assuming that the highest leaf rate of trees is 100%, a leaf rate of 20% to 60% denoted an unhealthy growing tree, and 0% to 20% denoted a dying tree. To take seasonal differences into account, these characteristics were assessed in both summer (November-December) and winter (August).

The distribution of vegetation at Site 1 was mapped using a measure, compass, GPS, and an infrared distance meter (Fig. 3). Topographic profile 1 was mapped by measuring 156 points along a 400-m transect, and Topographic profile 2 was mapped by measuring 97 points along a 500-m transect. Soil profile and soil water were measured in pits that were 1 to 2 m deep. Wood fragments were dated by ^{14}C (radiocarbon) dating methods. Soil water was measured in soil moisture by volume using a Hydro-sense soil moisture meter (Campbell Scientific Ltd.).

^{14}C dating was performed by Beta Analytic Inc., Miami, Florida, USA. Small samples (Table 1: samples 3–5, 8) were dated by accelerator mass analysis (AMS). The ^{14}C date is presented as conventional ^{14}C age. In the case of modern samples (samples 1–6) from 1950, the dates were obtained by comparison between

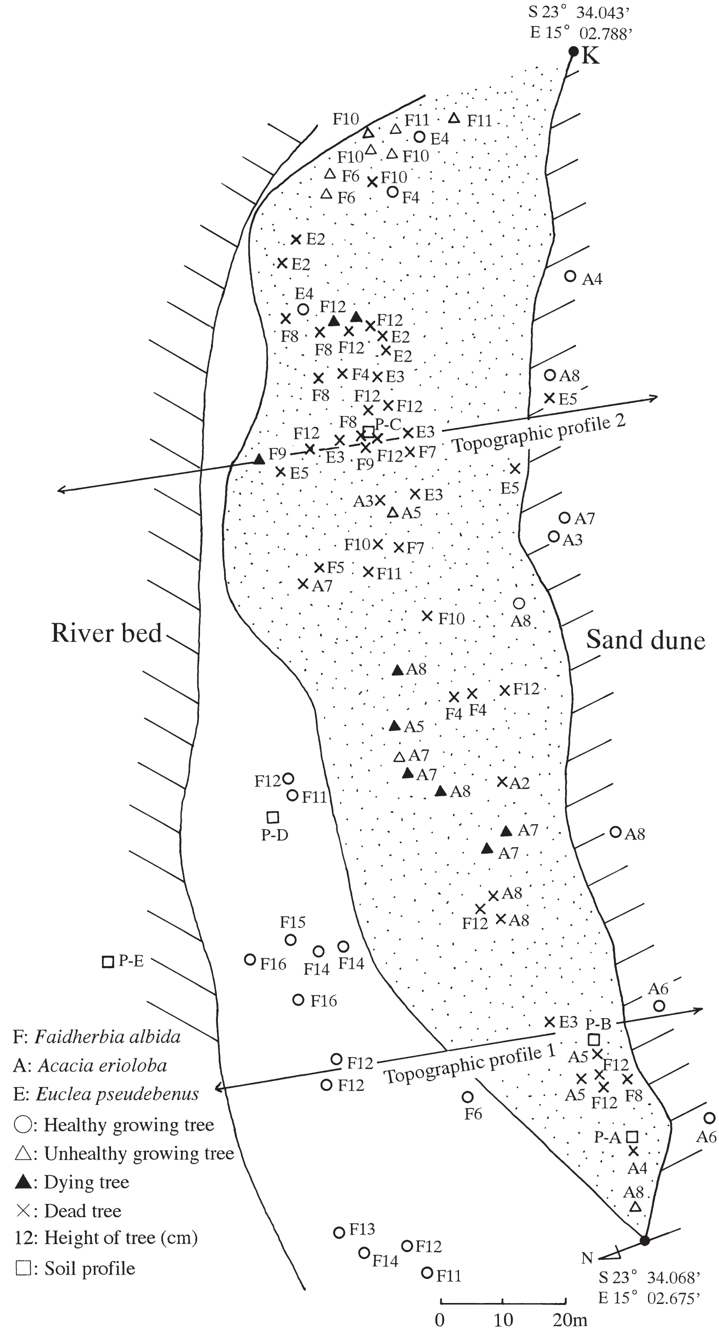

Fig. 3. Topography and distribution of trees at Site 1.
Dotted area denotes river bank composed of dune sand. K is a reference point used to measure movement of the sand dune. Classification of trees is the same as in Fig. 5.

Table 1. ^{14}C dates of tree samples (conventional ^{14}C age).

Sample number	Material	Meathod	^{14}C data (yr BP)	$\delta^{13}C$ (permil)	Laboratory code number (Beta-)
1	Wood	Radiometric	118.0 ± 0.7 pMC*	−28.4	170934
2	Wood	Radiometric	131.5 ± 0.8 pMC*	−24.5	170935
3	Wood	AMS	121.1 ± 0.5 pMC*	−26.2	170938
4	Wood	AMS	133.8 ± 0.7 pMC*	−26.9	170936
5	Wood	AMS	134.6 ± 0.7 pMC*	−26.4	170937
6	Wood	Radiometric	103.5 ± 0.7 pMC*	−25.4	170939
7	Wood	Radiometric	380 ± 90	−25.4	170940
8	Plant material	AMS	140 ± 40	−25.1	170941
9	Wood	Radiometric	220 ± 50	−26.3	170942

*: Modern (percentage is from the modern standard).
Radiometric: Radiometric dating. AMS: Accelerator Mass Spectrometry.

the ^{14}C concentrations of wood fragments and global data (1950–2000) (Nakamura *et al*., 1987; Levin & Kromer, 2002; etc.). (Fig. 22). This method assumes a global tendency for a gradual increase of ^{14}C concentration in the atmosphere owing to fission and fusion bomb detonation, coming to a peak in 1964–1965, and a decrease in atmospheric ^{14}C concentrations thereafter. Therefore, two dates, before and after 1964–1965, were identified from concentration values. For dating of the dead trees, the ends of branches were chosen, as they were the last to grow.

RESULTS AND DISCUSSION

I. Extensive Tree Death and the Environment

Figure 1 shows the locations of extensive tree death along the Kuiseb River; four such areas (Sites 1 – 4) were confirmed for a 50 km stretch along the Kuiseb River.

The distribution of dead trees at Site 1 (Fig. 4) is shown in Fig. 3. Trees growing on the small terrace appeared to be almost dead or dying. On both the slope below the terrace and the slope of the sand dune, the trees were still alive except for one *Euclea pseudebenus*. For the relationship between tree height and trunk diameter at breast height in healthy trees, values were bimodally distributed (i.e., low and high) (Fig. 5). Large trees were distributed on the slope below the terrace, and small trees were located on


Fig. 4. Dead trees at Site 1.

the slope of the sand dune. Trees growing on the slope below the terrace had a larger diameter than expected diameter for their height.

In the two topographic profiles along the transects, there are depressions between the terrace and the slope of the sand dune (Figs. 6 & 7). The soil profiles P-A, P-B, and P-C (Figs. 8 & 21) are clearly different in the color and soil texture from the alluvial deposits (Fig. 9) of the slope below the terrace (Figs. 6 & 7).

In the quadrant of Site 2 (30 m × 210 m) (Fig. 10), although there are many

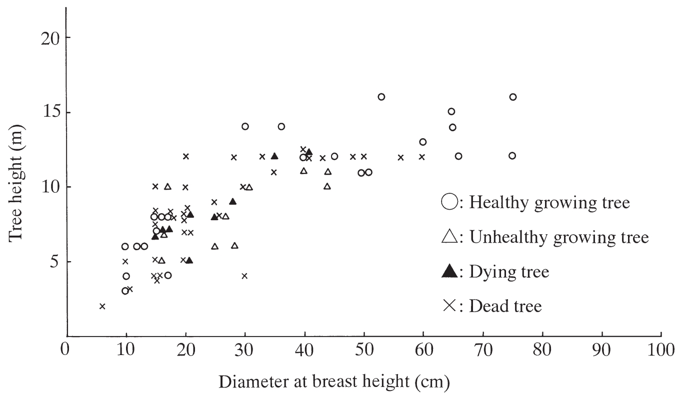

Fig. 5. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 1. Vital status of trees was divided into four groups: healthy growing tree, unhealthy growing tree, dying tree, and dead tree. Assuming that the highest leaf rate is 100%, a leaf rate of 20% to 60% characterized the unhealthy growing trees and that of 0% to 20% characterized dying trees. To take seasonal differences into consideration, assessments were made in summer (November –December) and winter (August).

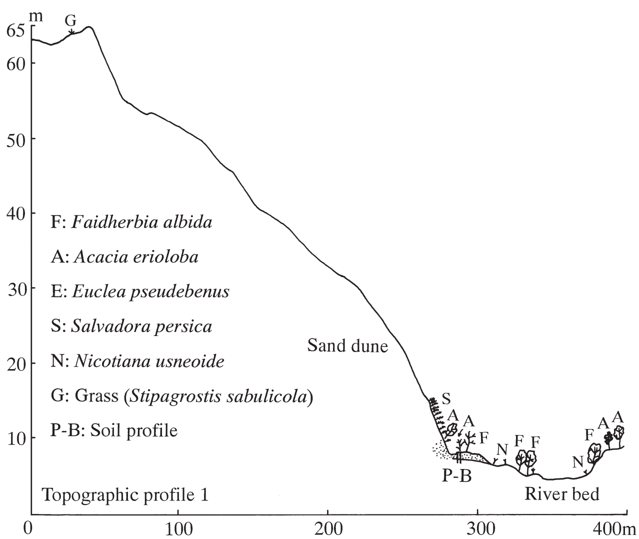

Fig. 6. Topographic profile 1 at Site 1 (Fig. 3).

dead trees, healthy trees appear to be growing well (Fig. 11). In the quadrant of Site 3 (18 m × 120 m) (Fig. 12), almost all of the trees appear to be dead, but two small growing trees appear to have regenerated recently (Fig. 13). In the quadrant of Site 4 (25 m × 60 m) (Fig. 14), it is thought that the forest may be reviving because regenerated trees are mixed among the dead trees (Fig. 15). In the control quadrant of Site 5 (15 m × 75 m), on the slope below the terrace, there are very few dead trees, and almost all trees are large in both height and diameter (Fig. 16).

At Sites 2 through 4, it appears that sand eroded from the sand dune has been deposited with the alluvial sediments, as assessed by an examination of the topography, soil color, and soil texture of the terrace occupied by dead trees.

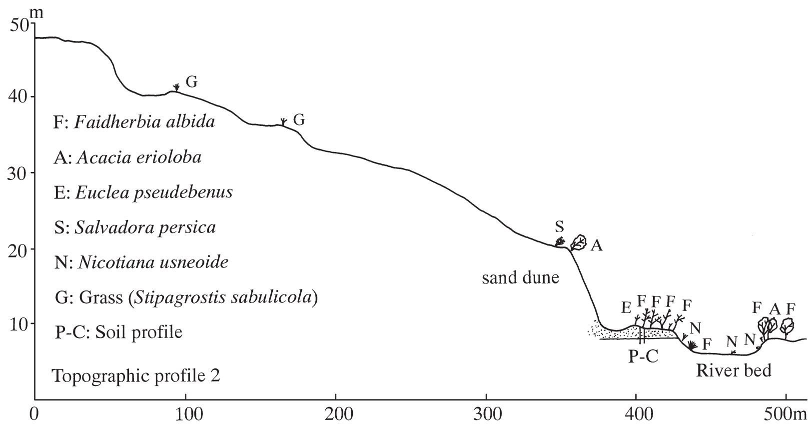

Fig. 7. Topographic profile 2 at Site 1 (Fig. 3).

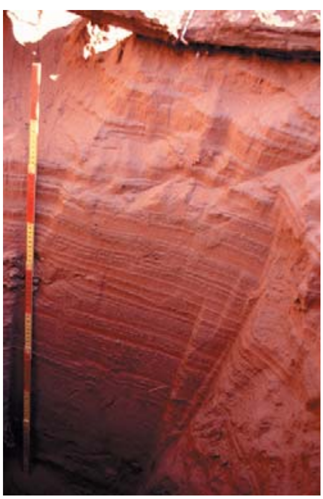

Fig. 8. Soil profile of the small terrace (river bank) composed of dune sand.

Fig. 9. Soil profile of the slope below the terrace (river bank).

Fig. 10. Dead trees at Site 2.

Fig. 12. Dead trees at Site 3.

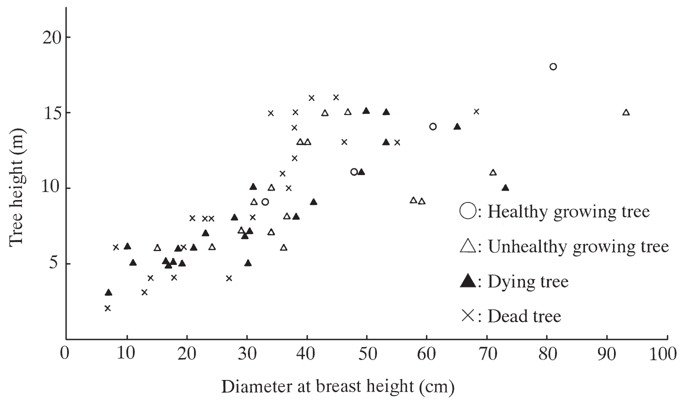

Fig. 11. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 2. Classification of trees is the same as in Fig. 5.

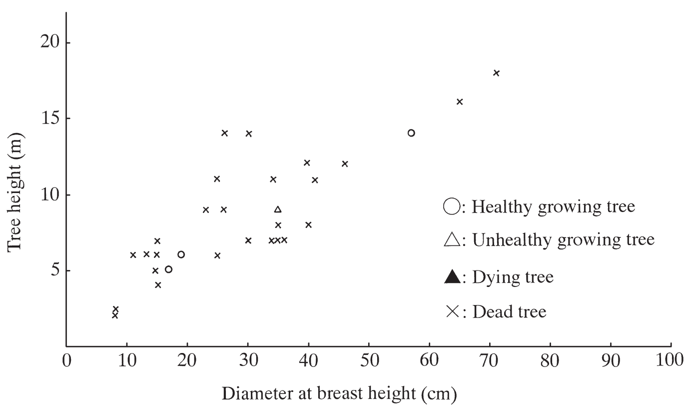

Fig. 13. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 3. Classification of trees is the same as in Fig. 5.

II. Causes of Tree Death

Comparisons of areas with many dead trees at all four sites revealed a common characteristic: they are transitional areas where a northward protrusion of the southern shore is followed by a southward protrusion of the northern shore along the course of the river, in proximity to a sand dune (Fig. 1). It can be surmised that extensive tree death may have been caused by sand deposition resulting from flood formation of sand banks, from dunes projecting into the river, or by erosion of the noses of

Fig. 14. Dead trees at Site 4.

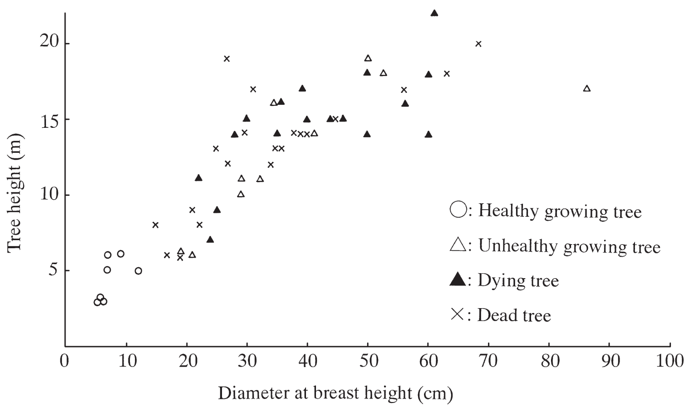

Fig. 15. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 4. Classification of trees is the same as in Fig. 5.

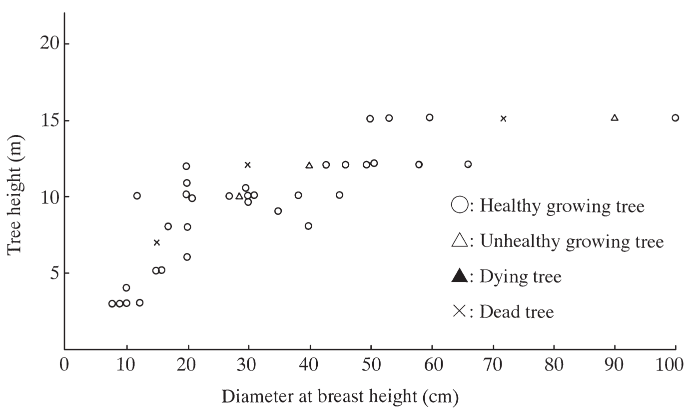

Fig. 16. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 5 (control site). Classification of trees is the same as in Fig. 5.

Fig. 17. End of sand dune (point K, Fig. 5) (December 1, 2002).

Fig. 18. End of sand dune (August 10, 2003).

Fig. 19. End of sand dune (November 30, 2003).

Fig. 20. End of sand dune (August 5, 2004).

advancing sand dunes and subsequent downstream deposition.

To monitor sand dune advance, a reference location was established at point K, as shown in Fig.3. A pole was planted at the end of a sand dune on November 29, 2002 (Fig. 17). By March 1, 2003, the pole was not buried at all and no sand dune movement was observed. By August 10, 2003, the pole was buried to a depth of 60 cm and the sand dune had advanced 100 cm horizontally (Fig. 18). By November 30, 2003, the pole was buried to a depth of 70 cm and the sand dune had advanced 145 cm from its initial position (Fig. 19). By August 5, 2004, the pole was buried to a depth of 130 cm and the sand dune had advanced 220 cm from its initial position (Fig. 20). Therefore, it was concluded that the sand had advanced discontinuously, and that its rate of advance was 120–145 cm/year (November 2002–August 2004).

The upper soil of the forest along the river was found to be a dull yellowish-brown (10YR5/3, 10YR5/4, 10YR4/3), and the soil of the sand dune was found to be bright reddish-brown (5YR5/6) or orange, or a dull brown (7.5YR5/4) (Fig. 21). Soil color thus can be used as an index of its origin. At Site 1, soil profiles from the terrace (river bank) formed by redeposit of dune sand (P-A, P-B, and P-C; Figs. 3 & 8), the slope below the terrace (P-D, Figs. 3 & 9), and the river bed (P-E, Fig. 3) were compared (Fig. 21). In profile P-A, bright reddish-brown (5YR5/6) sand deposits of a thickness of 70 cm were found to overlie dull yellowish-brown (10YR5/4) sandy loam. In profile

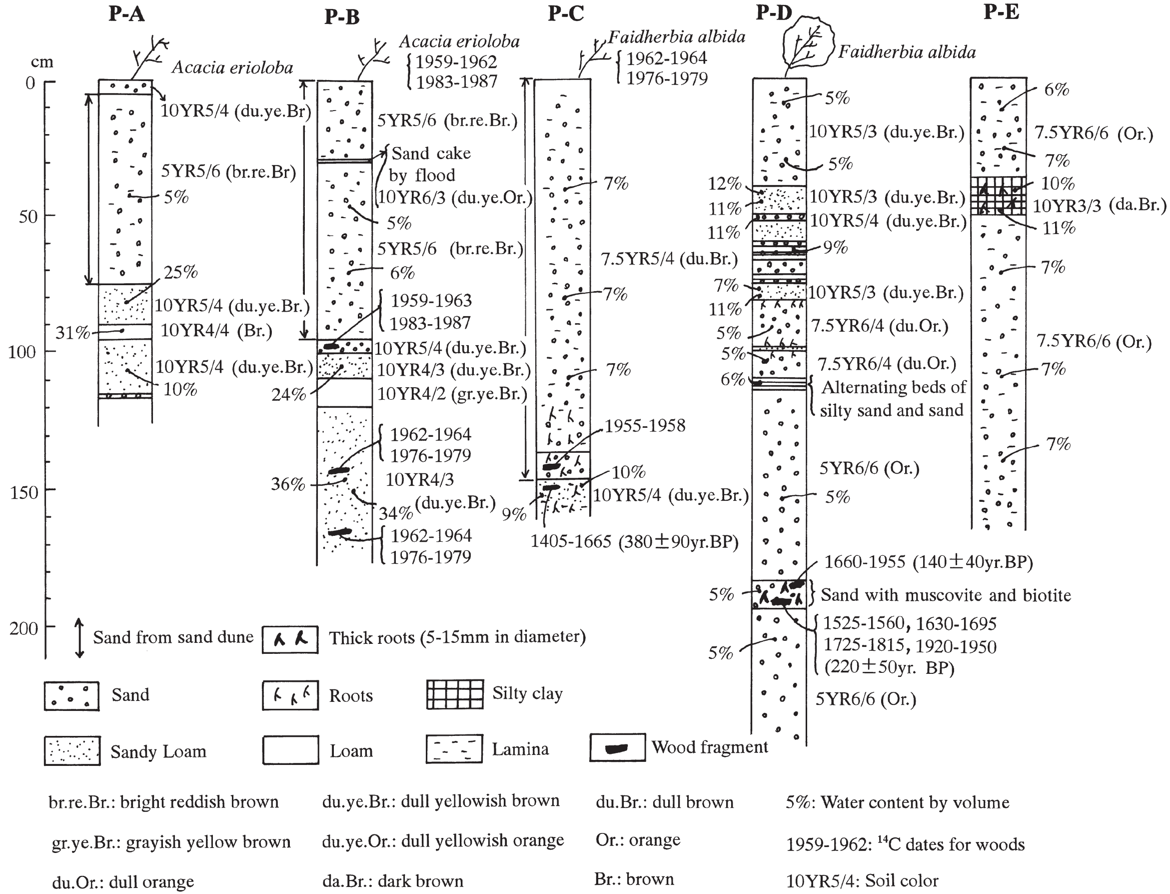

Fig. 21. Soil profiles at Site 1 (Fig. 3). P-A, P-B, P-C: Soil profiles in areas covered by dead trees; P-D: Soil profile in an area covered by healthy growing trees; P-E: Soil profile in the river bed.

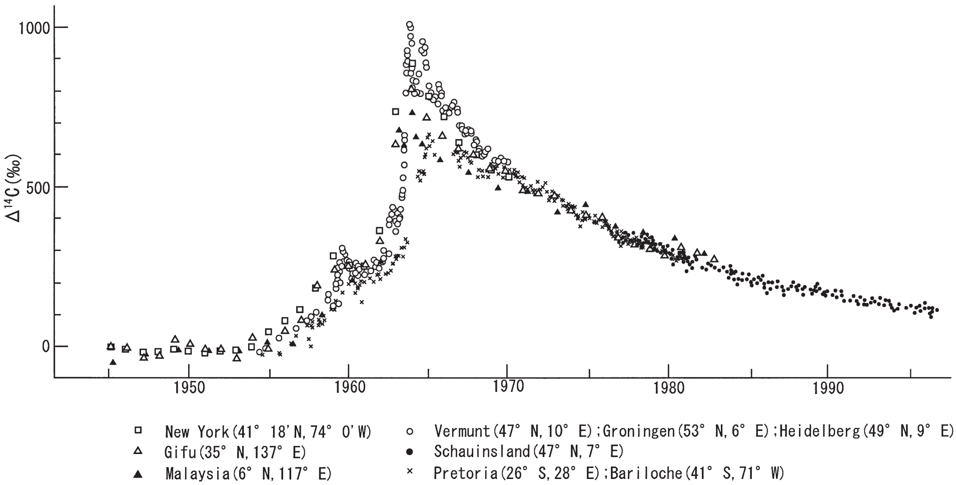

Fig. 22. Fission/fusion bomb-induced ^{14}C concentration variation in the global atmosphere.

Fig. 23. Adventive roots at 35-cm depth from the land surface.

P-B, bright reddish-brown (5YR5/6) sand deposits of a thickness of 100 cm were found, and the date of a wood fragment directly beneath the sand was estimated at 1959–1963 or 1983–1987 by ^{14}C concentration (Table 1, sample 3; Figs. 21 & 22).

The upper layers of soil profiles (P-A, P-B, P-C) including almost no litter suggest that the terrace has been recently formed by remarkable redeposit of dune sand (Fig. 21). The date of the dead trees was estimated as being 1959–1962 or 1983–1987 by ^{14}C concentration (Table 1, sample 1; Figs. 21 & 22). In soil profile P-B, it is reasonable to suggest that the sand was deposited over the wood fragment by floods in the 1960s to 1970s, from its date (1959–1963), and from the fact that the trees appear to have died from 1983 to 1987. In soil profile P-C, dull brown (7.5YR5/4) sand deposits of a thickness of 150 cm overlie dull yellowish-brown (10YR5/4) sandy loam. A wood fragment at the bottom of the sand layer had an estimated date of 1955–1958 by ^{14}C concentration (Table 1, sample 6; Figs. 21 and 22), and the date of dead trees was estimated at 1962–1964 or 1976–1979 by ^{14}C concentration (Table 1, sample 1; Figs. 21 & 22). In soil profile P-C, it appears that sand was deposited over the wood fragment by floods in the 1960s to 1970s, and that the trees died in 1976–1979. Although most trees on the terrace (bank) appear dead, some trees are not. One tree (Fig. 3, ΔA5) with relatively abundant leaves was found to have adventive roots at a depth of 35 cm from the land surface (Fig. 23). Adventive roots may play a protective role against tree death caused by sand deposition. This will be a subject of future research.

In soil profile P-D, where dune sand is absent, dull yellowish-brown (10YR5/3) soil can be observed and the trees are still alive. Although soil moisture (water content by volume) is below 10% in the sand layer from the surface to 70 to 150 cm in profiles P-A, P-B, and P-C of the terrace (bank) covered by many dead trees, it is over 10% at 40 cm deep in profile P-D (Fig. 21). In profile P-E of the river bed, orange (7.5YR6/6) sand can be observed.

III. Flood Fluctuations and Tree Death

In Gobabeb, the number of days of flood (all running water is regarded as

Fig. 24. Kuiseb River flood. (January 18, 2004: by Andrea Schmitz). Kuiseb River has usually no water.

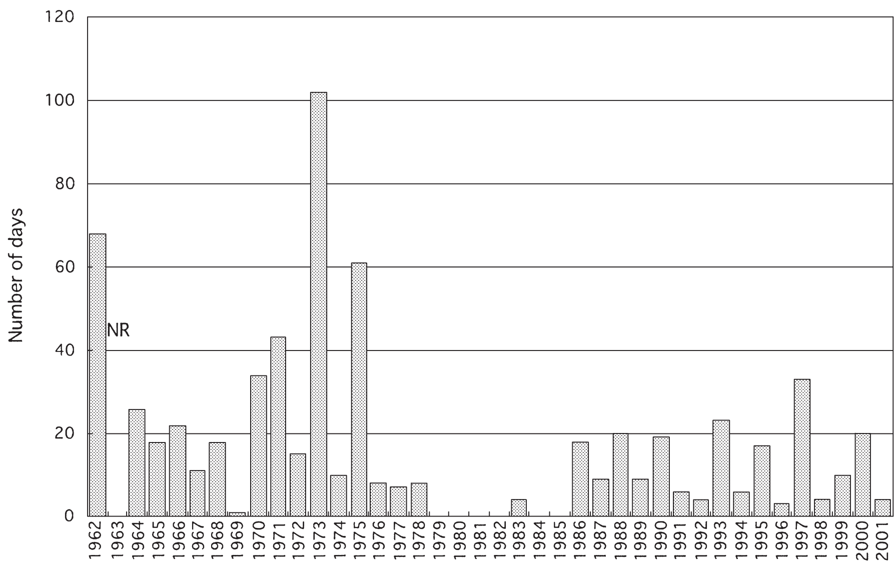

Fig. 25. Summary of Kuiseb River floods at Gobabeb, 1962–2001.
1962–1984: Seely *et al.*, 1981; Ward & Brunn, 1985. 1985–2001: from data of the Desert Research Foundation of Namibia.

flood) (Fig. 24) for the Kuiseb River was 33.0 days/year from 1962 to 1975. It was 9.2 days/year from 1976 to 2001, a decrease to one third of the 1962–1975 value (Fig. 25). The 1976–1987 date, estimated by ^{14}C methods as the date range of extensive tree death, coincides with the period when the number of flood days was very low. Until 1975, each successive flood washed away the sand deposited by the previous flood, and the trees did not die. For 12 years, from 1976 to 1987, the number of flood days decreased to 52 in total (4.3 days/year). For seven years, from 1979 to 1985, very little flooding occurred, and many trees died, perhaps because of sand deposition or a drop in the water table caused by a decrease in flooding.

CONCLUSIONS

The Kuiseb River in the Namib Desert marks the transition between stony desert and sand desert (i.e., sand dunes). Although forest is distributed along the course of the river, several areas are characterized by extensive tree death. These locations have the topography of small terraces (river bank), on which sand from dunes has been redeposited to a thickness of 1 m by flood. The upper layer of terrace indicates the same soil color and soil texture as the sand dune. Therefore, it is considered that sand of terrace is the materials redeposited from sand dune. The other characteristic common to all locations of extensive tree death is that they are in transitional areas where a northward protrusion of the southern shore is followed by a southward protrusion of the northern shore along the course of the river, and in proximity to a sand dune. It is reasonable to suggest that the cause of tree death has been sand redeposition from flooding, i.e., erosion of the advancing sand dunes and subsequent downstream sand deposition. The rate of sand dune advancement was measured at 120 to 145 cm/year for the period November 2002 to August 2004.

The dates of extensive tree death appear to be 1976–1987 by comparison of ^{14}C concentrations of the ends of dead tree branches and global ^{14}C concentration data (1950–2000). The dates of extensive sand deposition appear to be the 1960s to 1970s, as judged by the dating of wood fragments just underneath the orange sand layer. Although the number of days of flood at Gobabeb for the Kuiseb River was 33.0 days/year from 1962 to 1975, it was only 9.2 days/year from 1976 to 2001, a decrease to one third of the value in the period from 1962 to 1975. Until 1975, each successive flood appears to have washed away the sand deposited by the former flood, and the trees survived. For 12 years, from 1976 to 1987, the total number of flood days decreased to 52 (4.3 days/year); this period coincides with the dates of extensive tree death, as estimated by ^{14}C dating. For seven years, from 1979 to 1985, very little flooding occurred, and many trees died, perhaps because of sand deposition or a drop in the water table, owing to the decrease in floods.

The pastoral Topnaar people live along the Kuiseb River. The forest along the river provides shade, shelter, firewood, and food for goats as well as humans. The death of trees in this area is thus a serious problem. It is important, therefore, that the relationship between tree death and environmental changes be monitored and analyzed.

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